

Manuscript Draft

Manuscript Number: STOTEN-D-05-00823R1

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Article Type: Wetland Pollutant Special Issue Paper

Keywords: Biochemical oxygen demand; Detention; Gully; Nitrate; Road runoff; Storm water

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Design comparison of experimental storm water detention systems treating concentrated road runoff

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Abstract

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1. Introduction

1.1. Sustainable Drainage Systems

‘SUDS’ is the acronym for Sustainable (Urban) Drainage System (British English) or also known as Best Management Practice (American English). A singular or series of management structures and associated processes designed to drain surface runoff as part of a sustainable strategy to predominantly alleviate capacities in existing conventional drainage systems in an urban environment is defined as SUDS (Butler and Davies, 2000; CIRIA, 2000; Scholz, 2006; SEPA, 1999).

New developments proposed for Brownfield sites or on the periphery of urban developments may be unable to obtain planning permission, if existing local sewers have no spare capacity for storm water drainage, and if the storm water discharge from the proposed site cannot be controlled. In the absence of suitable watercourses that can accommodate direct storm water discharges, alternative technologies such as ‘at source’ storm water storage and detention systems are required (Butler and Davies, 2000; Scholz, 2006).

Many existing catchments in Scotland (e.g., Glasgow and Edinburgh), which are served by combined sewerage, have the potential to increase local sewer capacity by disconnecting storm water at other sites within developed parts of the catchment (D’Arcy and Frost, 2001). Diversion of urban runoff before it enters the combined sewer into locally based storage devices such as the Atlantis Water Management Limited detention cell system has been shown to be a viable approach in many cases (Butler and Davies, 2000; CIRIA, 2000; Scholz, 2006).

Optimising the maintenance of SUDS structures is currently one of the greatest management problems. Mowing grass and removing litter and debris are the most time-consuming and therefore costly maintenance tasks (Jefferies et al., 1999; McKissock et al., 1999; Scholz, 2003).

Maintenance of all public above-ground SUDS structures is usually the responsibility of the local authority (The Stationary Office, 1998). These above-ground structures are defined as swales, ponds, basins and any other ground depression features. In contrast, the maintenance of below-ground SUDS structures is usually the responsibility of the local water authority. Below-ground SUDS structures include culverts, infiltration

trenches, filter strips and below-ground detention systems (Butler and Davies, 2000; CIRIA, 2000; Nuttall, 1998; Scholz, 2006).

Storm water runoff is usually collected in gully pots that can be viewed as simple physical, chemical and biological reactors. They are particularly effective in retaining suspended solids (Bulc and Slak, 2003). Currently, gully pot liquor is extracted once or twice per annum from road drains and transported (often over long distances) for disposal at sewage treatment works (Butler et al., 1995; Memon and Butler, 2002). A more sustainable solution would be to treat the entire road or car park runoff locally in potentially sustainable storm water detention systems such as below-ground storage systems and storm water ponds (Guo, 2001) reducing transport and treatment costs. Furthermore, runoff treated with storm water detention systems can be recycled for irrigation purposes.

Below-ground storm water storage and detention systems are defined as a sub-surface structure designed to accumulate surface water runoff, and where water is released from as may be required to increase the flow hydrograph. The structure may contain aggregates with a high void ratio or empty plastic cells and act also as a water recycler or infiltration device (Butler and Parkinson, 1997; Scholz, 2006).

A below-ground storm water detention system comprises a number of components forming a structure that is designed to reduce storm water flow. The system captures surface water through infiltration and other methods. The filtered storm water is stored below-ground in a tank. The water is often cleaned and filtered before it is infiltrated or discharged to the sewer or watercourse via a discharge control valve. The system benefits include runoff reduction of minor storms, groundwater recharge and pollution

reduction. This detention system is predominantly applied in new developments (Scholz, 2006).

The effect of varying organic loading rates on the treatment performance of the complex biomass within most filter systems used for primary treatment is unknown. Moreover, an experimental study is required to assess the passive treatment performance of storm water detention systems.

1.2. Project purpose

The aim is to advance knowledge and understanding by formulating design guidelines for vertical-flow storm water detention systems treating road runoff predominantly by extended storage in a cold climate such as the Southeast of Scotland. The objectives are to assess

1. the function of turf (absent *versus* present) and different aggregates such as Ecosoil as components of a primary treatment filtration stage before the below-ground detention systems; and
2. the overall passive treatment performance of vertical-flow storm water detention systems.

2. Materials and methods

2.1. System design and operation

Five detention systems (Table 1 and Fig. 1) were located outdoors at The King's Buildings campus (The University of Edinburgh, Scotland) to assess the system performance during a relatively cold spring and summer (31/03-19/08/04; Table 2). Inflow water, polluted by road runoff, was collected by manual abstraction with a 2 l beaker from randomly selected gully pots on the campus and the nearby main roads.

Five storm water detention systems based on plastic cells (boxes with large holes) wrapped in standard inert geotextile were used. Virtually any geotextile complying with the corresponding national standard could be used. Each system had the following dimensions: height = 85 cm, length = 68 cm and width = 41 cm. Two plastic cells on top of each other made up one detention system (Fig. 1). The bottom cell (almost 50% full at any time) was used for water storage only. The top cell contained the aggregates. Different packing order arrangements of inert single size aggregates and plant roots were used in the systems (Table 1) to test for the effects of gravel (6 and 20 mm diameter single size layers), 1.5 mm diameter sand, 2 mm diameter Ecosoil, block paving and turf on the water treatment performance. Apart from System 5, all remaining systems were unplanted. Systems 2 to 5 contained additional media: System 2 contained sand. System 3 comprised sand and Ecosoil. System 4 contained sand, Ecosoil and block paving. Finally, System 5 comprised Sand, Ecosoil and turf. In comparison to all other systems, natural aeration of System 4 was restricted due to block paving.

The filtration system was designed to operate in vertical-flow batch mode. Manual flow control was practised. Gully pot liquor compares well with concentrated road runoff (by a factor of at least 30 depending on gully pot spacing), and was used in the experiment as a 'worst case scenario' liquid replacing road runoff. All detention

systems were approximately twice per week watered with 10 l gully pot liquor as slow as possible, and drained by gravity afterwards to encourage air penetration through the soils (Table 1) (Cooper et al., 1996; Gervin and Brix, 2001). The relative quantity of gully pot liquor used per system was approximately $3.6 \times$ the mean annual rainfall volume to simulate a 'worst case scenario'. The hydraulic residence times were in the order of one hour. Biodegradation was enhanced by encouraging natural ventilation of the aggregates from the top via the natural air, and from the bottom via the air pocket above the storage water and between the aggregates (Fig. 1). Considering industrial-scale systems, vertical ventilation pipes should be installed to encourage passive ventilation as well.

2.2. Analytical methods

The five-day @ 20 °C ATU biochemical oxygen demand (BOD) was determined in the inflow and outflow water samples with the OxiTop IS 12-6 system (Wissenschaftlich-Technische Werkstätten (WTW), Weilheim, Germany), a manometric measurement device. The measurement principle is based on measuring pressure differences estimated by piezoresistive electronic pressure sensors. Nitrification was suppressed by adding 0.05 ml of 5 g/l N-Allylthiourea (WTW Chemical Solution No. NTH 600) solution per 50 ml of sample water.

Concerning the analysis of nutrients in the liquid phase, oxidised aqueous nitrogen was determined in all water samples as the sum of nitrate-nitrogen and nitrite-nitrogen. However, nitrite-nitrogen concentrations were significantly low (data not shown). Nitrate was reduced to nitrite by cadmium and determined as an azo dye at 540 nm

(using a Perstorp Analytical EnviroFlow 3000 flow injection analyser) following diazotisation with sulphanilamide and subsequent coupling with N-1-naphthylethylenediamine dihydrochloride (Allen, 1974).

Ammonia-nitrate and ortho-phosphate-phosphorus were determined by automated colorimetry in all water samples from reaction with hypochlorite and salicylate ions in solution in the presence of sodium nitrosopentacyanoferrate, and reaction with acidic molybdate to form a phosphomolybdenum blue complex, respectively (Allen, 1974). The coloured complexes formed were measured spectrometrically at 655 and 882 nm, respectively, using a Bran and Luebbe autoanalyser (Model AAIII).

A Whatman PHA 230 bench-top pH meter (for control only), a Hanna HI 9142 portable waterproof dissolved oxygen (DO) meter, a HACH 2100N turbidity meter and a Mettler Toledo MPC 227 conductivity, total dissolved solids (TDS) and pH meter were used to determine DO, turbidity, and conductivity, TDS and pH, respectively. An ORP HI 98201 redox potential meter with a platinum tip electrode HI 73201 was used to measure the redox potential. Composite water samples based on 2 litre of sample water taken randomly at a minimum of four sample locations and/or times were analysed. All other analytical procedures were performed according to the American standard methods (APHA, 1998).

Concerning the analysis of major nutrients in Ecosoil (aggregate supplied by Atlantis Water Management Limited), 2 ml sulphuric acid (strength of 98%, v/v) and 1.5 ml hydrogen peroxide (strength of 30%, v/v) were used as an extraction media (Allen, 1974). Approximately 0.1 g of each dried sample and the associated digestion media were placed in a tube and heated at 320°C for 6 h. Aliquots were taken and digests were made up to 100 ml with distilled water.

For analysis of total nitrogen, the following procedure was adopted: Ammonium (present in the digest) reacts with hypochlorite ions generated by alkaline hydrolysis of sodium dichloroisocyanurate. The reaction forms monochloroamine which reacts with salicylate ions in the presence of sodium nitroprusside to form a blue indophenol complex. This complex is measured colorimetrically at 660 nm using a Bran & Luebbe autoanalyser (model AAIII).

For analysis of total phosphorus, the following procedure was used: Orthophosphate (present in the digest) reacts with ammonium molybdate in the presence of sulphuric acid to form a phosphomolybdenum complex. Potassium antimonyl tartrate and ascorbic acid are used to reduce the complex, forming a blue colour, which is proportional to the total phosphorus concentration. Absorption was measured at 660 nm using a Bran & Luebbe autoanalyser (model AAIII).

For the analysis of total potassium, the digest was analysed by a flame atomic absorption spectrometer (Unicam 919, Cambridge, UK) at a wavelength of 766.5 nm and with a bandpass of 1.5 nm. Standards were prepared in 100 ml flasks using 2 ml concentrated sulphuric acid and 1.5 ml hydrogen peroxide (30% v/v) and made up to mark with de-ionised water. Caesium at a concentration of 100 mg/l was added to both standards and digests to overcome ionisation.

Metal concentrations were determined in the raw gully pot liquor and the outflow waters from the experimental rig on 16 June 2004. Water samples for metal determinations were stored at -19°C until analysis.

Concerning the analysis of Ecosoil and grass cuttings, composite samples (usually at least four sub-samples) were randomly collected and stored at -10°C prior to analysis. After thawing, approximately 2.5 g of each sample was weighed into a 100 ml digestion

flask to which 21 ml of hydrochloric acid (strength of 37%, v/v) and 7 ml of nitric acid (strength of 69%, v/v) were added. The mixtures were then heated on a Kjeldahl digestion apparatus (Fisons, UK) for at least 2 h. After cooling, all solutions were filtered through a Whatman Number 541 hardened ashless filter paper into 100 ml volumetric flasks. After rinsing the filter papers, solutions were made up to the mark with deionised water. The method was adapted from the section 'Nitric Acid-Hydrochloric Acid Digestion' (APHA, 1998).

An Inductively Coupled Plasma Optical Emission Spectrophotometer (ICP-OES) called TJA IRIS and supplied by ThermoElemental (USA) was used to analyse selected wastewater, Ecosoil and grass cutting samples. The purpose was to economically screen samples to determine various trace element concentrations and potential contaminants. Analytical precision (relative standard deviation) was typically 5-10% for three individual aliquots.

No replicates were analysed unless stated otherwise in the standard methods (APHA, 1998). However, replicate samples were stored in the freezer, and revisited for specific variables where unexplained outliers were determined. If required these outliers were either replaced or ignored.

3. Results and discussion

3.1. Comparison of costs

The overall capital and maintenance costs were estimated for each detention system for the first year of operation. Maintenance included litter removal and grass cutting, and was based on an area of 1000 m². Material prices were requested for a volume of 100 m³ per aggregate to obtain realistic figures for a scaled-up detention system (industrial operation size). It follows that the five system configurations have standardised cost ratios of approximately 1.0 : 1.1 : 1.2 : 1.3 : 1.6 based on Edinburgh prices in March 2004.

The actual prices are subject to negotiations and fluctuations on the market (i.e. labour costs, quantities ordered and transportation costs). Costs for sand, gravel, Ecosoil and block paving are likely to be similar to their transportation costs (e.g., between £20 and £35 per m³) for most small sites. Moreover, block paving costs depend heavily on the expenditure for skilled labour; i.e. a square meter may require up to 30 min laying time depending on the type of block paving and specifications for the corresponding purpose. Turf may be as cheap as £1.5 per square metre. The detention cells provided by Atlantis Water Management Limited may be sold for £4 per cell depending on the distributor. However, the corresponding installation costs are considerable higher. A detention cell system for a medium sized car park (500 to 1000 m²) in Edinburgh, for example, costs between £5,000 and £15,000 depending on the specific site, specifications and contractor.

3.2. Inflow water quality

Table 2 summarises the inflow water quality. The standard deviations for all inflow parameters (except for DO, pH and temperature) are high (Table 2) due to the random

selection of gully pots and seasonal variations (Butler and Parkinson, 1997; Scholz, 2004).

The gully pot liquor was less polluted in summer than in spring. For example, BOD, SS and turbidity in summer were 42, 33 and 46% lower, respectively (Table 2). There are various reasons for this including the observation that the higher temperature in summer compared to spring results in a faster biodegradation rate within the gully pot (Table 2). Moreover, the retention time of the gully pot liquor in summer is likely to be longer than in spring due to less frequent rainfall events. A longer retention time correlated positively with a higher biodegradation rate (APHA, 1998; Butler and Davies, 2000; Scholz, 2004).

3.3. Comparison of outflow water qualities

The overall filtration performance figures are summarised in Table 3 that should be compared with Table 2. Figure 2 shows 'real' inflow and outflow concentrations for all detention systems for BOD, SS and nitrate-nitrogen, respectively. Considering the relatively high standard deviations of most inflow water quality variables, and the only indirect relationships between inflow and outflow concentrations over time (i.e. buffer function of the large storage tank), it would be misleading to show mean outflow concentrations.

Reduction efficiencies for BOD and SS (Table 3) are comparable to findings reported elsewhere (Bulc and Slac, 2003; Scholz, 2004) for highway runoff treatment with constructed wetlands. The reductions of BOD (Table 3 and Fig. 2a) were acceptable for most systems, if compared to minimum American and European

standards for the secondary treatment of effluent. Biochemical oxygen demand in contrast to SS (Table 3 and Fig. 2a,b) outflow concentrations did not exceed the US thresholds of 30.0 mg/l, respectively (Tchobanoglous et al., 2003). However, some European standards or those of individual regional agencies (Cooper et al., 1996; Lim et al., 2003; Shutes et al., 2001) are more stringent; e.g. BOD <20 mg/l. The BOD outflow concentration was also lower than the UK standard for secondary treated wastewater of 20 mg/l (Table 3).

A regression analysis has shown that BOD, ammonia-nitrogen, nitrate-nitrogen and ortho-phosphate-phosphorus can be estimated with conductivity and total dissolved solids using a second order polynomial equation. For example, concerning BOD, nitrate-nitrogen and ammonia-nitrogen with conductivity, the corresponding coefficient of determination (r^2) for Filter 4 are 0.60, 0.71 and 0.76, respectively. The application of these relationships for internal water quality control purposes is likely to result in the reduction of sampling effort. However, statistical relationships between other variables were not significant.

Furthermore, it has been suggested that mature and viable microbial biomass, in contrast to aggregates with high adsorption capacities (e.g., Ecosoil) and turf, is responsible for the high overall filtration performances (Cooper et al., 1996; Scholz and Martin, 1998). However, it is difficult to classify objectively a biological system as mature without having undertaken intensive microbiological work.

Finally, analysis by ICP-OES of selected inflow and outflow samples for a suite of cations showed that all waters generally contained low concentrations of heavy metals. Measured elemental concentrations were either low (barium, calcium, magnesium and manganese), close to the detection limit of 0.014 mg/l for iron, for example, and for

most heavy metals (e.g., aluminium, copper and cadmium) below the detection limit (0.2, 0.029 and 0.1 mg/l, respectively). Dissolved zinc (detection limit: 0.006 mg/l) was the pollutant measured with the highest corresponding concentration. The mean inflow concentration for zinc was 0.14 mg/l and the corresponding outflow concentrations were 0.07 mg/l (standard deviation: 0.05 mg/l).

3.4. Ecosoil and turf

The commercial product Ecosoil is rather an inert inorganic aggregate than an organic soil. The analysis shows that it does not contribute to elevated nutrient concentrations due to very low total nitrogen, total phosphorus and total potassium concentrations of 65, 46 and 1367 mg/kg, respectively. In comparison, a recent soil quality analysis for areas in Glasgow, where SUDS were considered for implementation, indicated total nitrogen, total phosphorus and total potassium concentrations of 1612, 605 and 4562 mg/kg (Scholz et al., 2005). It follows that Ecosoil does function only as a very weak fertiliser, and that it is therefore unlikely to contribute to eutrophication after the release of the treated storm water to the nearby watercourse.

Furthermore, Ecosoil contained only trace amounts of heavy metals (except for aluminium): 1036, 24 and 7 mg/kg dry weight of aluminium, zinc and nickel, respectively. All other metal concentrations were below the detection limit of the instrument. However, even the aluminium concentrations are similar to values reported elsewhere for urban soil (Scholz et al., 2005).

The influence of turf (Filter 5; Fig. 1) on the organic matter content of the outflow was studied. The BOD and SS concentrations within the outflow from the planted system compared to the unplanted gravel and sand systems were similar (Tables 2 and 3). However, BOD in the outflow of System 5 was lower compared to all other systems.

Moreover, grass on top of Filter 5 (Fig. 1) was cut when the length was greater than 10 cm for optical reasons and to reduce the overall nutrient load. Total nitrogen, total phosphorus and total potassium concentrations were 3001, 640 and 6909 mg/kg fresh weight. The presence and harvesting of grass seemed to have a positive effect on the overall nitrate-nitrogen outflow concentration that was lower for System 5 if compared to the remaining systems (Tables 2 and 3; Fig. 2c).

3.5. Analysis of variance

Table 4 summarises analysis of variance findings for selected water quality outflow variables concerning selected detention system combinations. The overall data sets were also sub-divided into seasonal data sets.

The threshold for statistically significant findings is $P < 0.05$. It follows that pairs of data associated with $P \geq 0.05$ can be regarded as not significantly different. For example, the most simple and complex systems (System 1 and Systems 4 or 5, respectively; Table 1) are similar in term of their BOD and SS removal efficiencies.

3.6. Nutrient transformations

Ammonification, nitrification and denitrification are the three dominant nitrogen transformations that were partly quantified by measuring ammonia-nitrogen and nitrate-nitrogen (Tables 2 and 3). Ammonification is the conversion from organic-nitrogen to ammonia-nitrogen. Ammonia-nitrogen is used by micro-organisms and turf (Filter 5; Fig. 1) for new biomass development (Memon and Butler, 2002). This explains the higher reduction of ammonia in planted compared to unplanted storm water detention systems (see above and Tables 2 and 3).

Ammonification is slower in anaerobic than in aerobic aggregates because of the reduced efficiency of heterotrophic decomposition in anaerobic environments. Therefore, it was important to drawdown the water table completely after watering to allow oxygen to penetrate into the deeper filter-like layers of aggregates on top of the storage tank (Table 1). Ammonification also depends on pH being within an optimum range of approximately 6.5 to 8.5 (Kadlec and Knight, 1996), which was the case throughout the experiment (see also Table 2).

Furthermore, nitrification transforms ammonia-nitrogen to nitrate-nitrogen. This transformation has two steps. Ammonia-nitrogen originates from decomposed grass, organic litter (e.g., leaves and faeces) and dead microorganisms (e.g., bacteria and protozoa). It was therefore important to cut and harvest turf (grass cuttings) regularly. Nitrification is important because turf takes up nitrate-nitrogen preferentially to ammonia-nitrogen (Tables 2 and 3). However, this transformation requires oxygen during the drawdown periods. Denitrification is the process in which nitrate-nitrogen is reduced to gaseous nitrogen. This transformation is supported by facultative anaerobes. These organisms are capable of breaking down oxygen-containing compounds such as nitrate-nitrogen to obtain oxygen in the anoxic environment that is likely to have

occurred at the stagnant bottom of the storage tank and within the less well aerated layers of aggregates (see above and Table 1) during warm periods. However, Fig. 2c indicates that the denitrification process was not completed. It follows that the retention times were likely to be too short.

4. Conclusions

Five-day @20°C biochemical oxygen demand (BOD) outflow concentrations were below the UK threshold of 20 mg/l for secondary treated wastewater. The storm water detention system did show signs of overloading resulting in relatively high suspended solids (SS) and nitrate-nitrogen concentrations, and further treatment would be required. Moreover, denitrification was not completed, and longer retention times are therefore suggested. Nitrate-nitrogen was lower in the outflow of the planted system (turf on the top).

Gully pot liquor (concentrated storm water runoff) in relative quantities exceeding three times the mean annual rainfall was used for all systems. Therefore, it is likely that the SS concentration would be much lower in the field under real in comparison to the tested 'worst case scenario' conditions.

An analysis of variance indicated that there was no significant difference between most systems in terms of their treatment performance (e.g., BOD and SS) despite of their different set-ups. It follows that all systems regardless of their pre-treatment function as covered wastewater stabilization ponds.

Sampling effort can potentially be reduced for internal water quality control purposes by using relationships derived from a regression analysis between expensive variables that can be substituted by low-cost ones. For example, BOD can be replaced by conductivity for internal control purposes.

Ecosoil did contain relatively low concentrations of nutrients and metals (except for aluminium). It follows that higher investment costs for more complex systems are not justified based on a water quality analysis alone. However, further research concerning the potential hydraulic and structural benefits of additional aggregates such as Ecosoil is required.

Acknowledgements

The authors wish to acknowledge the support provided by Dr P. Anderson, Dr K. V. Heal, Mr. A. Gray and Mr. J. Mormon (all of The University of Edinburgh), and Mr. N. Cooper (Atlantis Water Management Limited). Sponsors: Atlantis Water Management Limited (storm water detention systems and Ecosoil) and Marshalls Public (block paving).

References

Allen SE. Chemical Analysis of Ecological Materials. Blackwell, Oxford, 1974.

- APHA. Standard Methods for the Examination of Water and Wastewater. 20th edn., American Public Health Association (APHA), AWWWA and WEF, Washington DC, 1998.
- Bulc T, Slak AS. Performance of constructed wetland for highway runoff treatment. Wat Sci Tech 2003;48(2):315-22.
- Butler D, Davies JW. Urban Drainage. E & FN Spon, London, 2000.
- Butler D, Parkinson J. Towards sustainable urban drainage. Wat Sci Tech 1997;35(9):53-63.
- Butler D, Xiao Y, Karunaratne SHPG, Thedchananamoorthy S. The gully pot as a physical, chemical and biological reactor. Wat Sci Tech 1995;31(7):219-28.
- CIRIA. Sustainable Urban Drainage Systems: Design Manual for Scotland and Northern Ireland. Report C521, Construction Industry Research and Information Association (CIRIA), Cromwell Press, London, 2000.
- Cooper PF, Job GD, Green MB, Shutes RBE. Reed Beds and Constructed Wetlands for Wastewater Treatment. WRc plc., Swindon, 1996.
- D'Arcy B, Frost A. The role of best management practices in alleviating water quality problems associated with diffuse pollution. Sci Tot Env 2001;265(1-3):359-67.
- Gervin L, Brix H. Reduction of nutrients from combined sewer overflows and lake water in a vertical-flow constructed wetland system. Wat Sci Tech 2001;44(11-12):171-76.
- Guo Y. Hydrologic design of urban flood control detention ponds. ASCE J Hydrolog Eng 2001;6(6):472-79.
- Jefferies C, Aitken A, Mclean N, MacDonald K, McKissock G. Assessing the performance of urban BMPs in Scotland. Wat Sci Tech 1999;39(12):123-31.

- Kadlec RH, Knight RL. Treatment Wetlands. CRC Press, Boca Raton, Florida, 1996.
- Lim PE, Tay MG, Mak KY, Mohamed N. The effect of heavy metals on nitrogen and oxygen demand reduction in constructed wetlands. *Sci Tot Env* 2003; 301(1-3):13-21.
- McKissock G, Jefferies C, D'Arcy BJ. An assessment of drainage best management practices in Scotland. *J Ch Inst Wat Env Managem* 1999;13(1):47-51.
- Memon FA, Butler D. Assessment of gully pot management strategies for runoff quality control using a dynamic model. *Sci Tot Env* 2002;295(1-3):115-29.
- Nuttall PM, Boon AG, Rowell MR. Review of the design and Management of Constructed Wetlands. Report 180, Construction Industry Research and Information Association, London, 1998.
- SEPA. Protecting the Quality of our Environment – Sustainable Urban Drainage: An Introduction. The Stationary Office, London, 1999.
- Scholz M. Sustainable operation of a combined flood-attenuation wetland and dry pond system. *J Ch Inst Wat Env Managem* 2003;17(3):171-75.
- Scholz M. Treatment of gully pot effluent containing nickel and copper with constructed wetlands in a cold climate. *J Ch Inst Wat Env Managem* 2004;79(2):153-62.
- Scholz M. Wetland Systems to Control Urban Runoff. Elsevier, Amsterdam, 2006.
- Scholz M., Martin RJ. Control of bio-regenerated granular activated carbon by spreadsheet modelling. *J Chem Tech Biotechnol* 1998;71(3):253-61.
- Scholz M, Morgan R, Picher A. Storm water resources development and management in Glasgow: two case studies. *Int J Env Stud* 2005;62(3):263-82.

Shutes RE, Revitt DM, Scholes LNL, Forshaw M, Winter B. An experimental constructed wetland system for the treatment of highway runoff in the United Kingdom. Wat Sci Tech 2001;44(11-12):571-78.

Tchobanoglous G, Burton FL, Stensel HD. Wastewater Engineering: Treatment and Reuse (4th edn, revised). Metcalf & Eddy Inc. and McGraw Hill Companies Inc., New York, 2003.

The Stationery Office. Sewerage (Scotland) Act 1968. The Stationery Office Books, London, 1998.

Table 1
Packing order of the storm water detention systems; all building materials are inert

Height (mm)	System 1	System 2	System 3	System 4	System 5
861-930 (top)	Air	Air	Air	Block paving and 6 mm gravel (within spaces)	Air
791-860	Air	Air	Air	1.5 mm sand and 2 mm Ecosoil	Turf
751-790	Air	Air	1.5 mm sand and 2 mm Ecosoil		1.5 mm sand and 2 mm Ecosoil
711-750	Air	Sand	1.5 mm sand and Ecosoil	1.5 mm sand and 2 mm Ecosoil	1.5 mm sand and 2 mm Ecosoil
661-710	6 mm gravel 20 mm gravel	6 mm gravel 20 mm gravel	6 mm gravel 20 mm gravel	6 mm gravel 20 mm gravel	6 mm gravel
451-660					20 mm gravel
437-450	1.5 mm sand	1.5 mm sand	1.5 mm sand	1.5 mm sand	1.5 mm sand
431-436	Standard geotextile	Standard geotextile	Standard geotextile	Standard geotextile	Standard geotextile
201-430	Air	Air	Air	Air	Air
0-200 (bottom)	Water	Water	Water	Water	Water

Table 2

Gully pot liquor (inflow to systems): water quality variables (31/03-19/08/04)

Variable	Unit	Number of samples	Mean	SD ^a	Mean (spring ^b)	Mean (summer ^c)
BOD ^d	mg/l	30	37.8	55.30	50.3	29.4
Nitrate-nitrogen ^e	mg/l	34	1.0	1.54	0.5	1.4
Ammonia-nitrogen	mg/l	34	2.1	1.85	2.4	1.9
Ortho-phosphate-phosphorus	mg/l	34	0.2	0.12	0.1	0.2
Suspended solids	mg/l	30	596.5	1430.40	725.6	483.5
Total solids	mg/l	30	442.8	848.58	311.4	518.9
Turbidity	NTU	35	81.3	81.67	108.0	58.7
Dissolved oxygen	mg/l	33	3.2	1.47	2.9	3.3
pH ^f	-	35	6.99	0.286	6.79	7.16
Redox potential	mV	35	178.0	110.62	106.2	238.5
Conductivity	µS	35	224.7	223.25	338.5	128.9
Temperature (air)	°C	34	18.0	3.92	16.2	19.4
Temperature (gully pot)	°C	34	17.4	4.66	14.6	19.7

^astandard deviation; ^b31/03-21/06/04; ^c22/06/04-19/08/04; ^dfive-day @ 20°C N-Allylthiourea biochemical oxygen demand;^eincludes nitrite-nitrogen; ^fcalculation based on measurement values; na = not available.

Table 3

Relative reduction (%) of outflow variables (31/03/04-19/08/04) with respect to the inflow variables shown in Table 2
change (%) per wetland system^a

Vari- ables	System 1			System 2			System 3		
	A ^b	B ^c	C ^d	A ^b	B ^c	C ^d	A ^b	B ^c	C ^d
BOD ^e	92	95	89	93	95	90	90	90	90
NO ₃ ^f	-1372	-1483	-1338	-1667	-832	-1918	-695	-482	-759
NH ₄ ^g	81	74	87	89	86	93	86	78	94
PO ₄ ^h	-74	16	-120	-64	12	-102	-33	12	-55
SS ⁱ	78	67	92	80	69	94	79	69	93
Turb ^j	91	92	90	90	91	89	84	81	88
Vari- ables	System 4			System 5					
	A ^b	B ^c	C ^d	A ^b	B ^c	C ^d			
BOD ^e	93	93	92	94	96	92			
NO ₃ ^f	-1020	-564	-1158	-393	-853	-254			
NH ₄ ^g	86	76	96	89	82	96			
PO ₄ ^h	-56	8	-88	-74	2	-113			
SS ⁱ	80	69	93	78	66	94			
Turb ^j	85	81	90	71	83	51			

^a Change (%) = $\frac{(in - out) \times 100}{in}$ (%), where in=inflow and out=outflow; ^b overall mean (31/03/04-19/08/04); ^c mean of the spring (31/03/04-21/06/04); ^d mean of the summer (22/06/04-19/08/04) ^e five-day @ 20°C N-Allylthiourea biochemical oxygen demand (mg/l); ^f nitrate-nitrogen (mg/l); ^g ammonia-nitrogen (mg/l); ^h ortho-phosphate-phosphorus (mg/l); ⁱ suspended solids (mg/l); ^j turbidity (NTU).

Table 4

Analysis of variance for selected outflow combinations (31/03/04-19/08/04)

Variables	System 1 and System 4			System 1 and System 5			System 4 and System 5		
	Y ^a	SG ^b	SR ^c	Y ^a	SG ^b	SR ^c	Y ^a	SG ^b	SR ^c
BOD ^d (mg/l)	0.91	0.22	0.06	0.08	0.60	0.07	0.25	0.16	0.84
Suspended solids (mg/l)	0.88	0.92	0.63	0.99	0.99	0.80	0.89	0.87	0.94
Total solids (mg/l)	0.56	0.07	0.64	0.36	0.34	0.75	0.89	0.36	0.50
Turbidity (NTU)	<i>0.01</i>	<i>0.00</i>	0.44	<i>0.00</i>	<i>0.03</i>	<i>0.00</i>	<i>0.01</i>	0.60	<i>0.00</i>
Dissolved oxygen (mg/l)	0.94	0.73	0.07	0.61	0.84	0.03	0.60	0.65	0.50
pH (-)	0.66	0.99	0.27	0.21	0.90	<i>0.00</i>	0.22	0.92	<i>0.03</i>
Redox potential (mV)	0.33	0.82	<i>0.02</i>	0.61	0.78	<i>0.01</i>	0.63	0.62	0.97
Conductivity (μS)	<i>0.00</i>	<i>0.00</i>	<i>0.02</i>	<i>0.01</i>	<i>0.00</i>	0.07	0.71	0.73	0.56

^ayear (overall data); ^bspring; ^csummer; ^dfive-day @ 20 °C N-Allylthiourea biochemical oxygen demand; includes nitrite-nitrogen. Note: Only P-values shown in italic indicate systems that are different from each other.

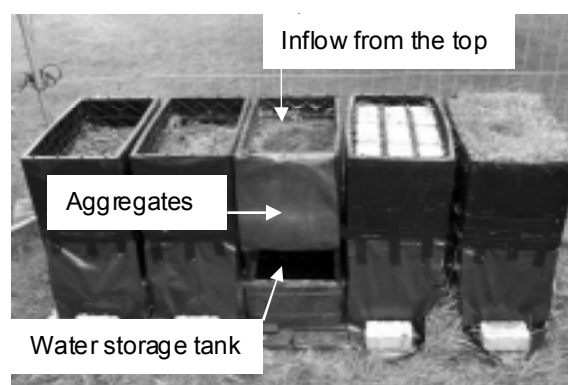
Figure captions

Fig. 1. Experimental storm water detention systems (The King's Buildings campus; The University of Edinburgh) on 1 July 2004: a) Systems 1 to 5; b) System 4 (partly covered with block paving); c) System 5 (covered with turf).

Fig. 2. (a) Five-day @ 20°C N-Allylthiourea biochemical oxygen demand, BOD (mg/l), (b) suspended solids, SS (mg/l), and (c) nitrate-nitrogen (mg/l) concentrations for the inflow and outflows of Systems 1 to 5.

Figure 1

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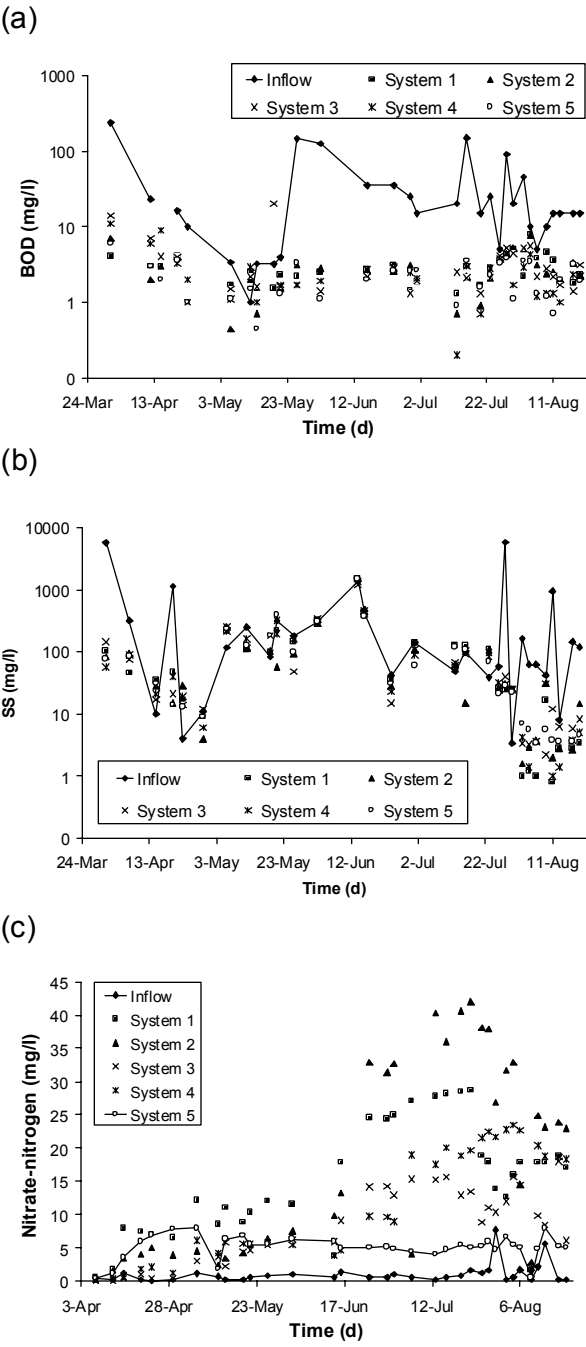


Figure 1 (original BMP file)

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Cover letter to the editor

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To you as the Guest Editor:

- The case study (including associated figures) and Table 1 have been removed.
- The paper has been shortened.
- All referee comments have been addressed (see below).

To Reviewer No. 1:

- Standard aggregates (e.g. sand and gravel) and building materials (e.g., geotextile) were used. They have been specified further, if essential to the interpretation of the findings. The referee should appreciate that inert materials themselves have virtually no direct impact on the water quality.
- Analytical detection limits for heavy metals have been listed.
- A brief discussion concerning real costs has been included.
- Composite samples were described further.
- Grading curves for sand and gravel are trivial (i.e. virtually meaningless) considering that single sizes were used as specified in the text and corresponding table.
- The paragraph concerning the regression analysis has been clarified, and unsubstantiated statements have been deleted. It follows that more diagrams are not necessary anymore.

To Reviewer No. 2:

- The filter material and the type of system have been detailed further in the abstract to make it more informative.
- Mean temperatures have been summarized in Table 2. An appropriate reference to Table 2 has been added in the text.
- The method statement on the redox potential has been corrected as suggested.
- Section 3.1 discusses now actual costs and should therefore be part of the section on results and discussions (i.e. not materials and methods). Referees should appreciate that it is virtually meaningless to specify aggregate costs considering that they depend on widely fluctuating variables such as location, labour and transport costs, for example. Differences might vary by one or two orders of magnitude!
- Statistical methods are now stated in the section on methods.
- As discussed in the text, it would be meaningless to state mean outflow concentrations considering the high standard deviations of most inflow water quality variables, and that inflow and outflow are not directly related to each other considering the buffer capacities of the large below-ground detention systems. Moreover, the paper would be unnecessarily long, and similar information would be presented at least twice (text, Tables 2 and 3, and Figure 2).

To Reviewer No. 3:

- The case study and associated material such as two figures has been removed.
- The key words have been revised as suggested.
- Table 1 has been deleted, and its content has been incorporated into the text.
- Figures 2 to 4 have been combined as suggested.